

OPTICAL PROPAGATION IN SEA ICE

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LONG-TERM GOAL

My goal is to develop new experimental and theoretical techniques for characterizing the optical properties of sea ice. Towards this goal, my effort has focused on measuring the beam spread function (BSF) of sea ice and applying diffusion theory to modeling light propagation and attenuation through bulk sea ice.

SCIENTIFIC OBJECTIVES

One objective is to demonstrate and establish the viability of a new method that I developed for measuring the complete beam spread function of sea ice. Because the BSF is equivalent to the point spread function (PSF), a related objective is to use the measured BSF to investigate the approach to the asymptotic light field generated by an embedded light source. My theoretical / modeling objective is to show that diffusion theory can be used to accurately model optical propagation through bulk sea ice.

APPROACH

The experimental approach for measuring the BSF [Maffione and Mobley, 1997] involves drilling two vertical holes in the sea ice. A cylindrical canister contain a laser is lowered into one of the holes with the source beam oriented horizontally. Another canister containing an irradiance detector is lowered into the other hole. The beam and detector are set at the same depth and aligned. The canister containing the laser is then rotated while the detector records the resultant irradiance. This irradiance, as a function of beam rotation angle, is equivalent to the beam spread and point spread functions. By lowering the canisters to various depths within the ice, profiles of the ice BSF/PSF are obtained. Moreover, the BSF/PSF can be measured as a function of pathlength by drilling the holes at various distances apart.

The measured BSF is modeled in three ways [Maffione and Mobley, 1997]. Using a least-squares regression, the data are fitted to a Lorentzian function of the form

$$\text{Lor}(\theta) = \frac{A}{[(\theta/\sigma)^2 - 1]}$$

where A is a constant and σ is the half-maximum angle. This functional form was found to be superior to a Gaussian function for all of the BSF data. For relatively long

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modeled by computing the asymptotic radiance distribution using estimated values of the sea ice inherent optical properties (IOP's). The estimated IOP's are then varied until the best agreement is found between the measured BSF's and the computed asymptotic radiance distribution, which is essentially an iterative inversion technique for obtaining the sea ice IOP's. The asymptotic light field was computed with Hydrolight, developed by Mobley [1995]. The third method for modeling the BSF is with a Monte Carlo program also developed by Mobley [1996] which simulates photon propagation for an embedded point light source.

In addition to modeling the BSF data using the three methods described above, I have been investigating modeling both solar and beam propagation in sea ice using the diffusion approximation [Maffione, 1997a; Maffione and Mobley, 1997]. One advantage of using the diffusion approximation is that it provides a simple, analytic formula that relates the diffuse attenuation coefficient to the phase function asymmetry parameter as well as the absorption and total scattering coefficients.

WORK COMPLETED

Because this annual reporting period was the final year of the EMPOSI DRI, the work completed consisted of analyzing field data and writing papers. Two papers were completed, submitted, and accepted for publication by Limnology and Oceanography. Two more papers, one with Mobley as first author and the other with Perovich as first author, were completed and submitted to the IEEE Transactions on Geoscience and Remote Sensing. We also have several papers in progress involving collaborations with Mobley and Cota.

RESULTS

The following result was rigorously derived from the radiative transfer equation as an asymptotic limit under the diffusion approximation [Maffione, 1997a]:

$$K_{\infty} = c\sqrt{3[1 - \omega_0 - g(\omega_0 - \omega_0^2)]}$$

where K_{∞} is the asymptotic diffuse attenuation coefficient, c is the beam attenuation coefficient, ω_0 is the single scattering albedo, and g is the phase function asymmetry parameter. Numerical calculations using Hydrolight show that this simple result is accurate for $\omega_0 > 0.95$ [Mobley and Maffione, 1996], which is the case for nearly all natural sea ice. By equating this diffusion result to a well known K equation presented by Kirk [1981] which he arrived at by statistically analyzing Monte Carlo radiative transfer simulations, Maffione [1997a] found that the regression parameter denoted by G in Kirk's equation could be expressed as

$$G = 3(1 - g) + 2(1/\omega_0 - 1)$$

ω_0 and g in his

simulations for highly turbid water into the above equation yielded a value of G that was within 2% of Kirk's reported value. This gratifying result shows that, for highly turbid water and sea ice, Kirk's numerically derived K relationship can be interpreted and understood within the context of photon diffusion theory. Conversely, applying Kirk's result to investigate the validity of the diffusion result reveals that the latter is accurate to within a few percent of the true value of K down to $\omega_0 \cong 0.97$, with errors gradually increasing as ω_0 decreases. Combining my diffusion theory results with Kirk's equation, and using values for K deduced from the BSF measurements of sea ice at Barrow, revealed that the asymmetry parameter g of the scattering phase function was in the range $0.9 \leq g \leq 0.95$ [Maffione and Mobley, 1997].

Another important result which emerged as part of my sea ice theoretical work in conjunction with my optical closure research was a proof that the asymptotic state is approached extremely more slowly for the light field created by an embedded source than it is for plane-wave solar illumination [Maffione, 1997b]. This phenomenon was first suggested by Maffione and Jaffe [1995] based on Monte Carlo calculations of a submerged point source. Because of the controversy created by this result, it was later checked and confirmed using independent Monte Carlo simulations by Mobley and Maffione [1996; 1997]. The theoretical proof that I derived firmly establishes the validity of this phenomenon and provides a simple formula for calculating the optical pathlength for the approach to the asymptotic state for a submerged light source based on the IOP's of the medium.

IMPACT/APPLICATIONS

The method I developed for measuring the BSF of sea ice can be directly applied to measuring the point spread function in shallow water which has immediate application to understanding and modeling beam propagation in the surf zone. This is important to using ocean lidar systems for bathymetry and other types of detection work in optically shallow water. I am currently building a prototype system for performing this PSF measurement based on the method developed on the sea ice program. This new method has many advantages over the classical method of using a CCD camera and Lambertian light source.

Kirk's K equation has been usefully applied to modeling highly turbid water, but the physical meaning of his regression parameter G was previously not understood. My work with diffusion theory for sea ice yielded an equation that directly explained the physical basis of Kirk's regression parameter, which is a very satisfying result that more firmly establishes the usefulness of simple K relationships.

My proof of the slow approach to the asymptotic state for the point spread and beam spread functions, and its confirmation through Monte Carlo modeling, has important implications to ocean lidar programs. For example, it has been commonly assumed that the lidar attenuation coefficient rapidly approaches the asymptotic state, and

thus it was often equated to the downwelling diffuse attenuation coefficient K_d . All too often, paradoxical discrepancies arose when comparisons were made of the lidar attenuation coefficient and *in-situ* measurements of K_d . The fact that I have now firmly established that the BSF approaches the asymptotic state extremely slowly should have a profound impact on ocean lidar studies.

TRANSITIONS

Because the results of this work are only now appearing in the literature, I am not aware of other investigators outside of the EMPOSI DRI who are using these results. However, I do expect that there will be several transitions involving the BSF methodology and the theoretical results in the near future.

RELATED PROJECTS

1. The asymptotic BSF/PSF theoretical work was also conducted in conjunction with
2. The numerical modeling work involving Hydrolight and Monte Carlo calculations is being carried out in close collaboration with C. Mobley who is separately funded by ONR.
3. Solar propagation through sea ice and its importance to biological production within and beneath sea ice is being conducted in collaboration with G. Cota and C. Mobley, both separately funded by ONR.

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